DYNAMICS OF LARGE PRECISION SPACE STRUCTURES FOR STRUCTURAL CONTROL

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ABSTRACT

This paper presents an overview of the challenges encountered in the prediction and ground test verification of structural dynamics for on-orbit control of large precision space structures. The inclusion of robustness in the structural design through the introduction of Adaptive Structures helps meet some of the challenges. Successes in laboratory and flight tests provide a guide regarding the achievable degree of robustness. The page limitation restricts the paper to a general discussion without figures and many references.

INTRODUCTION

Within the past few years, the National Aeronautics and Space Administration (NASA) sponsored a Control Structures Interaction (CSI) technology program with emphasis on demonstration of CSI on three different types of realistic testbeds (Aswani et al., 1991). One of the significant conclusions from the activity is the performance and stability of the controlled structures are highly dependent upon the knowledge of its structural characteristics, especially for precision structures with very low damping ($\approx$.05%). Based upon over 30 years of observing analytical predictions, ground tests, analysis/test correlations and limited flight data, the fidelity of the structural dynamic characteristics will not be adequate to meet many of the requirements for future missions. The control of large ($\geq$ 20-50 m) and precision ($\leq$ few microns) structures are not feasible (Wada and Garba, 1991). These limitations must be overcome.

One attractive approach is to introduce robustness into the design of structures that promises to reduce the overall cost in materials, engineering, manufacturing, assembly, processing, testing, and facilities while meeting the performance and stability requirements of large precision structures. Taguchi and Clausing, 1990, states that, "Quality is a virtue of design. The "robustness" of products is more a function of good design than of on-line control however stringent the manufacturing process. . .An inherent lack of robustness in a product design is the primary driver of superfluous manufacturing expenses.'! Ryan, 1993, also advocates introducing robustness into the design as a means of reducing cost, while producing reliability and meeting design requirements.

Introducing Adaptive Structures (Wada et al., 1990) into the structural design increases the robustness of its structural dynamics to reliably meet the design requirements. Also it increases the robustness of the design by providing solutions to unexpected dynamics responses or disturbances. One definition of Adaptive Structures are systems whose geometric and structural characteristics can be beneficially modified to meet mission requirements either through remote commands or automatically in response to internal or external stimulations. The design requires the direct integration of the actuators and sensors into load carrying structures.

BACKGROUND

Experience to Date

For many years, research on robust controller designs promised to account for many of the structural dynamics uncertainties. However, recently, for large precision structures with low damping and high modal density, the required fidelity in knowledge of the structural dynamic characteristics of the structure has been shown to be beyond reasonable expectations. The observation was deduced from experimentation performed by Fanson et al., 1990 and by many other researchers on other NASA testbeds.

For most weight constrained space systems developed to date, the structural dynamic mathematical models were verified by ground modal tests. These tests were invaluable based upon large discrepancies between the mathematical models and the test data for many systems. The "dream" of a few to eliminate the requirement for testing based upon the large finite element computer solution capability has not materialized. Many of the recent correlation results are no better than in the past, partially due to the complexity of recent structures. Mathematical models often predict non-existent dynamics, overlooks existing dynamics, and often do not attempt to predict non-linearities that appear in about 10% of the test modes. The art and science of mathematically modeling space structures evolved through its comparison with large motion structural dynamics test results. Namely, use of dynamic models for loads determination. Almost no experience exists on comparing micro-motion mathematical predictions of dynamics characteristics of non-monolithic structures with test data, since test data are non-existent.

The erroneous belief by many are that test data accurately represents the hardware. This conclusion cannot be refuted if only one set of data is measured. Nine different modal test approaches on a very linear Galileo spacecraft by Chen, 1984, resulted in 9 different sets of modal test data. The difference in results were attributable to the type of force excitation, the magnitude and direction of excitation, and the modal data extraction algorithm. Recent modal tests of other spacecraft seem to collaborate the observations made on Galileo. On one micro-wave antenna, tests were performed at the lowest feasible acceleration level with the modal test equipment. The lowest attainable level was .001g due to instrumentation limitations, whereas the desired level was .00001g. At lower amplitude levels, the environmental vibration levels have masks the experimental data. The data indicated strong non-linearities as a function of response levels. Recent data on a 5.0m x 13m x 4m radar antenna indicated large nonlinearities attributable to small gaps in joints.

Certain classes of space structures, such as large space antenna made of a stretch mesh over multiple radial ribs, exhibit unpredictable dynamics. The unpredictability is not related to mechanical non-linearities but a phenomenon referred to as mode localization. When structural elements with near equal modal characteristics (eg. the modes of each rib) are weakly coupled to each other, a small change in the structural properties of any rib results in dramatic changes in the system modal characteristics. Small changes can be a result of small differences in the dynamics of each rib, different masses associated with sensors/actuators and changes associated with the control forces. These dramatic changes were experimentally verified by Levine, 1992.

Often the analytical model is used to predict the dynamics of various operational states because the ground modal tests do not represent all aspects of the operational configurations. A mathematical model representing the ground test configuration is updated to correlate with the ground test data. The updated mathematical model is then modified to represent the various operational conditions. With current approaches for updating mathematical models, the mathematical models are improved but not to the fidelity necessary for controlling large precision structures.

Future Structural Requirements

Future structures require more accurate knowledge of the structural dynamic characteristics because they, are larger and more complex, have higher modal densities, require information in the micro-g vibration range, and are significantly affected by the one-g earths gravitational field. The validity of computer programs and modeling approaches to predict structural dynamic characteristics are based upon comparison of test data acquired for large motion dynamics. Almost no micro-dynamic test data exist for a non-monolithic structure. Limited experience indicates that the lowest reliable accelerations from current modal test systems and facilities are several orders of magnitude larger than the desired levels.

The one-g field preloads all the structural joints (several orders of magnitude greater than in-space) and thus during ground tests the structural responses are linear but in-space the structural response may exhibit non-linearities attributed to joint gaps. Experimental studies indicate that structures with joint gaps respond “chaotically.” Namely the response is random and bounded when excited by a deterministic excitation source. Unexpected low level responses, probably attributable to joint gaps, have been observed on many recent spacecraft such as Hubble Telescope and Upper Atmospheric Research Satellite. The current plan is to replace the Hubble Telescope solar arrays to alleviate the low level, but significant vibrations. Many spacecraft have experience "micro-phonics" low level vibrations adversely affecting the optical subsystem which were not predicted nor detected by ground tests.

Very limited data exist to verify differences between ground test data and flight data on well instrumented structures to help establish differences. A large deployable 3100cm X 400cm Solar Array Flight Dynamic Experiment (SADFE) revealed large discrepancies in modal damping and is reported by Shock, 1986. With the solar array in the sun, the array unexpectedly warped due to thermal gradients resulting in large errors between the predictions and flight modal frequencies. Recently, Crawley et al., 1993, reports on the comparison of ground test and flight test of the Middeck O-gravity Dynamics Experiment (MODE) . The beam configured truss structure consists of nine to eleven bays; the dimensions of each bay is 203mm X 203mm X 203mm. The structure is representative of one of the proposed Space Station configurations and includes an alpha joint in one test configuration. The flight data indicate large non-linearities as a function of amplitude and its correlation with ground test data indicates substantial differences.

Technology Deficiencies in Structural Dynamics

The current state-of-the-art modal ground test techniques are not capable of experimentally determining the dynamic characteristics of on-orbit large precision structures to the fidelity requirements. The author believes that if large precision structures for future missions cannot be ground tested, it will never be adopted for flight because the mathematical models are unreliable. Thus one of the major challenges to the structural dynamics research community is to overcome this dilemma. One approach is to introduce robustness in the design through the incorporation of Adaptive Structures concepts.

ROBUST DESIGN

The current approach to meet stringent structural dynamic requirements for large precision structures is the imposition of more precision and controls. Larger and more precise mathematical models; use of exotic materials; precision manufacturing and assembly; imposition of stringent environmental controls; sophisticated modal test equipment and algorithms; expensive facilities with o-g suspension systems and insensitive to thermal and air environment; precise analytical/test correlation algorithms; complex flight controllers and electronics; and extensive ground handling/storage controls are examples of additional impositions. These activities result in cost and schedule increases without necessary adding confidence in meeting the requirements. The inclusion of robustness into the structural design is required.

The inclusion of Adaptive Structures into the design adds robustness to help assure the structural dynamic characteristics requirements. The capability to adjust the structural dynamic characteristics during on-orbit operation can substantially relax all the requirements in the above paragraph. The degree of increased robustness is dependent on the adjustment range of the actuators and sensors of the Adaptive Structures. If the structural dynamic characteristics can be modified by 10-20 %, then knowledge of the dynamic characteristics of the passive system is only required to about 10-20%. The capability to improve linearity of the flight structure, increase structural damping, shift resonances frequencies, modify local stiffness, and provide dynamic isolation, during different phases of the spacecraft mission significantly reduces the complexities of the global control system while improving performance reliability. A robust design is also capable of counteracting unexpected dynamics and disturbances.

ADAPTIVE STRUCTURES

Wada and Garba, 1992 present an overview of the Adaptive Structures activities at the Jet Propulsion Laboratory that is primarily applicable to large precision space structures. The developments specifically relating to structural dynamics of large precision structure are summarized.

Structural damping is very important for the control of structures but cannot be analytically predicted nor are the ground test results reliable. For precision structures, often a lower bound for damping (less than 1% critical damping) is used for the design of the global controller. This assumption, significantly increases the complexity of the global controller design. Chen et al., 1990, adds robustness to the design by increasing and changing the damping of structural modes using active members. A robust approach to add damping to structures is to replace select structural members with active members (with actuators, sensors and controllers) at locations of maximum strain energy in the modes of interest. A co-located controller uses relative displacement and/or force of the active member as the feedback signal. The system is robust because when multiple active members are placed within the area of maximum strain energy, the active damping increases with the number of activated active members. Similarly, if an active member is turned off or fails, the level of active damping monotonically decreases. Values of passive structural damping levels of .05% were easily increased to 7% using active damping. A KC-135 flight experiment of a 12 meter truss demonstrated the capability to add damping to an ill-defined structure in O gravity using active members. For precision control, piezo-electric, electrostrictive, and magnetostrictive actuators have the required frequency bandwidth and resolution. Wada, 1993, summarizes the actuators used for precision control of space structures for Adaptive Structures.

Adjustments to the stiffness of active members located at areas of maximum strain energy of a mode, can be utilized to change the frequency of that mode. Experimentally, reduction in the active member stiffness of up to two orders of magnitude and an increase in the active member stiffness by up to a factor of two have been demonstrated.

The adjustment of structures in space requires knowledge of the structural dynamic characteristics of the structure from which changes are made. This process is referred to as on-orbit system identification. Most ground tests for system identification rely upon modal test approaches that excite the structure at maximum displacement locations using exciters suspended from the ceiling or mounted to the ground. The state-of-the-art modal test approaches are not directly applicable to structures in space. Chen and Fanson, 1989, used active members as exciters to identify the modal characteristics of the system. The modal data using active members seem to better represent the hardware because the direction and distribution of the forces during the test are more representative of the hardware in operation.

Kuo et al., 1990, helped establish the contribution and effectiveness of active members in a free-free structure using select active member as an excitor while adding active damping with other active members. The test demonstrates the feasibility of testing the structure in space using subsets of active members as exciters and other subsets to add damping and/or change modal frequencies.

The adaptability of the structural dynamics of the structure assumes the structure itself is somewhat linear and its dynamics are represented by linear modal characteristics. For precision structures, small gaps in joints that are disguised on the ground by preload in joints due to one-g can result in a structural system that responds chaotically in space. Namely the structures responds randomly when subjected to a deterministic input. With proper design, the non-linearity resulting from loose joints can be eliminated by preloading the joints using active members within an indeterminate structure, Wada and Utku, 1992.

The characteristics of the structure can be changed to meet the requirements, to allow more effective performance of a global controller, to make modifications to avoid "modal localization" and to account for unexpected dynamic phenomena. Structures do not have to be designed, analyzed, fabricated, and ground tested to stringent precision requirements because they can be adjusted in-space.

Research in Adaptive Structures has exponentially expanded and additional information is available in the conference proceedings edited by Wada, et al. , 1990, by Matsuzaki and Wada, 1991, and by Wada, et al., 1992.

CONCLUSION

Robustness is more a function of good design than of stringent design, engineering, fabrication and testing for structural dynamics that increases cost, schedule, and complexity in future missions. Also robustness is added to the design if on-orbit solutions to un-anticipated dynamic forcing functions or responses are available. The increase in robustness of a system through the introduction of Adaptive Structures has been experimentally demonstrated in the laboratory and in space. Stringent design requirements, engineering requirements, fabrication and testing are substantially relaxed and solution to unexpected events are available since the structure itself is adapted to meet the requirements during its operational life. Research and technology developments in Adaptive Structures promise to help meet the structural dynamic challenges for future large precision structures.

The application of Adaptive Structures appear only to be limited by the lack of creativity in design. Many new applications and related research issues are continually developing in all fields of engineering.

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REFERENCES

(1) Aswani, M., Wada, B. and Garba, J, 1991, "U.S. Perspective on Technology Demonstration Experiments for Adaptive Structure," Proceedings of the 30th IEEE Conference on Decision and Control, Brighton, UK, Dec. 11-13.

(2) Wada, B. and Garba, J. , 1991, "Ground Test Validation for Precision Structures ," Proceedings of the International Conference on Spacecraft Structures and Mechanical Testing, ESTEC, Noordwijk, The Netherlands, April 24-26.

(3) Taguchi, G. and Clausing, D., 1990, "Robust Quality," Harvard Business Review, January-February.

(4) Ryan, R., 1993, "Robustness, NASA Technical Paper 3336, Marshall Space Flight Center, Huntsville, Alabama, March.

(5) Wada, B., Fanson, J. and Crawley, E., 1990, "Adaptive Structures ," Journal of Intelligent Material Systems and Structures, Vol. 1, No. 2, April.

(6) Fanson, J., Chu, C., Smith, R., and Anderson E., 1990, "Active Member Control of a Precision Structure with an H Performance Objective," AIAA Paper No. 90-1224, Proceedings of the 1990 Dynamics Specialist Conference, Long Beach, CA April 5-6.

(7) Chen, J.C. ,1984, "Evaluation of Modal Testing Methods," AIAA Paper No. 84-1071, Proceedings of AIAA Dynamic Specialist Meeting, Palms Springs, CA.

(8) Levine-West, M. and Salama, M., 1992, "Mode Localization Experiments on a Ribbed Antenna," Proceedings of the 1992 SDM Conference, Dallas, TX, April.

(9) Shock, R.W., 1986, "Solar Array Flight Dynamic Experiment," NASA Technical Paper 2598.

(lo) Crawley, E., Barlow, M., Schoor, M., Masters, B., and Bicos, A ., 1993, "Zero-Gravity Measurement of the Modal Parameters of Space Structures," To Be Published.

(11) Wada, B.K. and Garba, J., 1992, "An Overview of Adaptive Structures Activities at JPL," Proceedings of Agard Specialist Meeting on Smart Structures for Aircraft and Spacecraft, Lindau, Germany. Oct. 5-7.

(12) Chen, G-S, Lurie, B.J. and Wada, B.K., 1990, "Active Member Control for Vibration Suppression in Truss Structures," <u>Intelligent Structures</u>, Elsevier Applied Science, London and New York.

(13) Wada, B.K., 1993, "Summary of Precision Actuators for Space Structures ," JPL Internal Document D-10659, Pasadena, CA,

March.
(14) Chen, J.C. and Fanson, J. L., 1989, "System Identification Test Using Active Members," AIAA Paper No. 89-1290, Proceedings of the AIAA 30th SDM Conference, Mobile, AL, April 3-5.
(15) Kuo, C.P., Chen, G.S., Pham, p., and Wada, B.K., 1990, "On-Orbit System Identification Using Active Members," AIAA Paper No. 90-1129, Proceedings of the 31st SDM Conference, Long Beach, CA, April 2-3.
(16) Wada, B.K. and Utku, s., 1992, "Adaptive Structure for Deployment/ Construction of Structures in Space," AIAA 92-2339, Proceedings of the 33rd AIAA SDM Conference, Dallas, TX, April 13-15.
(17) Wada, B.K., Fanson, J. and Miura, K., Editors, 1990, First Joint US/Japan Conference on Adaptive Structures, Technomics Publishing, Lancaster, PA.
(18) Matsuzaki, Y. and Wada, B.K., Editors, 1991, Second Joint Japan/US Conference on Adaptive Structures, Technomics Publishing, Lancaster, PA.
(19) Wada, B.K., Natori, M. and Breitbach, E., Editors, 1992, Third International Conference on Adaptive Structures, Technomics Publishing, Lancaster, PA.